Energy and Buildings 47 (2012) 68–73

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

LCA of low-energy flats using the Eco-indicator 99 method: Impact of insulation materials

Amaryllis Audenaert[a,b,*], Sven H. De Cleyn[b], Matthias Buyle[a]

[a] Department of Applied Engineering & Technology: Construction, Artesis Hogeschool Antwerpen, Paardenmarkt 92, BE-2000 Antwerpen, Belgium
[b] Department of Environment and Technology Management, Faculty of Applied Economics, UA, Prinsstraat 13, BE-2000 Antwerpen, Belgium

ARTICLE INFO

Article history:
Received 28 July 2011
Received in revised form
15 November 2011
Accepted 17 November 2011

Keywords:
Sustainable housing
Low-energy housing units
Life cycle analysis
Eco-indicator 99 method

ABSTRACT

Sustainable housing is receiving increasing attention by policy makers, architects, consumers and scholars. This study aims at enhancing our knowledge on the environmental impact of sustainable houses by performing a Life Cycle Assessment on a single case study. The case study is performed on a single low-energy building containing 19 flats using the Eco-indicator'99 method.

The results indicate that the choice of insulating materials has a significant impact on the eco-score of the design. The materials' production turns out to be by far the most influential, which bears the consequence that architects and consumers should focus on choosing the best materials in terms of eco-score instead of focusing on an environmental-friendly design. Waste recycling (if possible) has a lower eco-score compared to waste disposal (dumping or burning).

1. Sustainable housing

Academia, governments and industry are paying increasingly attention to sustainable housing technologies and construction methods to reduce our ecological footprint [1]. Although these efforts have increased our knowledge and understanding on the subject significantly, much research subjects in the domain remain untouched or underdeveloped, especially those at the intersection of different scientific domains, each touching upon a specific aspect of the topic. Little research (e.g. [2]) has addressed for example the economic implications of the sustainable housing concepts at the level of individual consumers and at societal level. Additionally, a considerable research gap emerges in the field, as the environmental impact of new building concepts and environmental-friendly housing technologies aiming at reducing the energy need for housing units has barely been evaluated. This study aims at contributing to our understanding of the viability of the sustainable housing concept as it is actually applied.

The aim of our study is to evaluate the environmental impact of housing units built according to low-energy standards through a single case study research. As case, a single building with 19 flats will be assessed through a Life Cycle Assessment (LCA) according to the Eco-indicator 99 method (cfr. Section 2 for more details on this method) and alternative material choices for external walls and internal and external insulation material will be compared within this setting. The average habitable surface of the flats is 85 m^2, with a *K*-value of 30 and an *E*-value of 60 [1]. The yearly energy demand for space heating accounts between 67 and 115 kWh/m^2 and the estimation of the average energy demand for daily use is between 100 and 115 kWh/m^2 primary energy. The flats are located in a single building which is Z-shaped and has three levels with a flat roof. The units each dispose of a living room, a kitchen, a storeroom, a bathroom and one, two or three bedrooms. The building plan of the ground level is presented in Fig. 1.

In the next sections, the concept of a Life Cycle Assessment is briefly described and more specific the Eco-indicator 99 method, which is used in this study. This method is applied to 19 housing units (flats) to calculate the ecological impact. Finally, different types of insulation and end-of-life scenarios are investigated and compared with the characteristics of the original design.

2. Analysis framework

A Life Cycle Assessment (LCA) is a methodology to analyse the environmental burden of processes and products during their whole life cycle, from cradle to grave [3–6]. According to the international standard series of ISO 14040, each LCA must consist of four steps to make it possible to compare different studies: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation [7]. The goal and scope defines the purpose, objectives and system boundaries. The second step is collecting all data regarding inputs, processes, emissions, etc. of the whole

* Corresponding author at: Department of Applied Engineering & Technology: Construction, Artesis Hogeschool Antwerpen, Paardenmarkt 92, BE-2000 Antwerpen, Belgium.
E-mail address: amaryllis.audenaert@artesis.be (A. Audenaert).

0378-7788/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2011.11.028

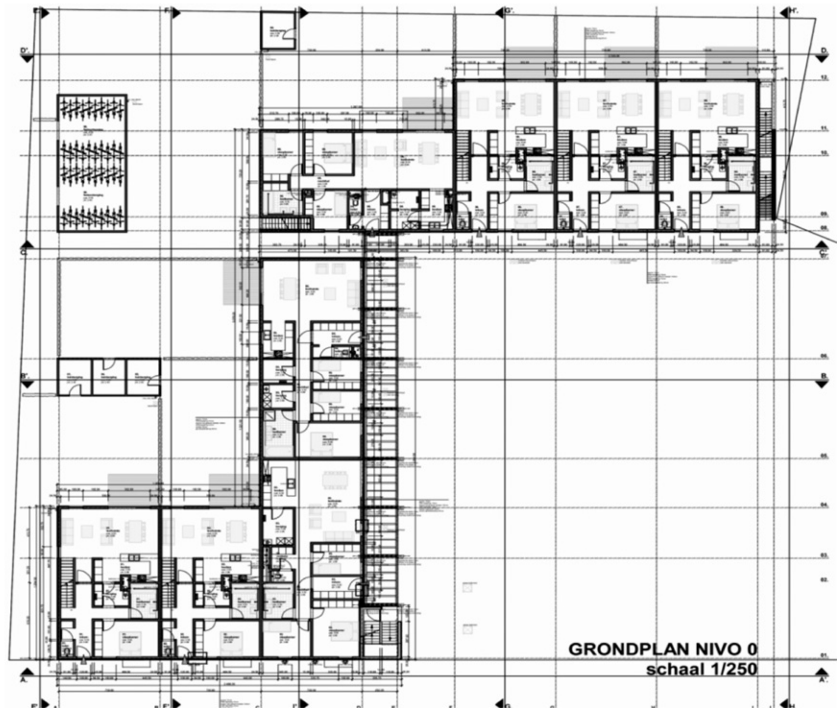

Fig. 1. Building plan of the ground floor.

life cycle. Third, the environmental impacts are quantified, based on the inventory analysis. This phase is composed of three mandatory steps: selection of impact categories, assignment of LCI results (classification) and modelling of category indicators (characterization). The final step is the interpretation of the results.

Although this is the global framework of a LCA, the exact technique is not defined. Depending on the nature of the research, different techniques can be used. A weakness of this approach is that different methods can generate different results, e.g. a narrow scope carbon footprint study versus studies with a set of more differentiated impact indicators [4,6].

In industrial processes, LCA is widely spread and used frequently to evaluate the environmental impact of products. In the building sector however, such a study is much more complex because of the long lifespan of a whole building (50–100 years [5,8]), a shorter lifespan of some elements, the use of many different materials and processes, the uniqueness of every building, the distance to factories, etc. [8]. Since the building process is less standardized than industrial processes, such a Life Cycle Assessment is a challenging task.

To quantify the environmental impacts, different kinds of indicators are possible, categorized in two groups: *problem-oriented* (mid-points) and *damage-oriented* (end-points) [9]. The first group classifies impacts into environmental themes such as global warming potential, acidification potential, ozone depletion potential, etc. This method generates a more complete picture of the ecological impact, but requires some knowledge of LCA to interpret the results.

The second group translates environmental impacts into issues of concern such as human health, natural environment and resources. The results of the latter are easier to understand, but there is the risk of losing transparency [10].

Within this research the Eco-indicator 99 is used, a damage-oriented method. Of all the emissions, extractions and land use in all processes, the damage they cause to human health, ecosystem quality and resources is calculated. At the end, these three categories are combined into a single score [11]. To do this, weighting factors are used to indicate the importance of each part (damage to resources 20%, human health 40%, ecosystems 40%). These factors are extracted out of a questionnaire with experts within the field of LCA [12]. As policymakers and public administrators often have the need for a practical tool, this single score method offers sufficient possibilities to analyse ecological impacts [13].

One of the advantages of the single score output of the Eco-indicator 99 method is that it makes it relatively easy to compare different building components. At the same time, the subjectivity of the weighting factors is one of the main weaknesses of this method.

Comparing results of a LCA is only meaningful when the subjects fulfill exact the same function. Such results are not a label of the sustainability of a product (or in this case a building). That is why within this research the Eco-indicator 99 is used to compare different variants of building components, subject to the same parameters, within the same lay-out and fulfill the same function.

3. Life Cycle Assessment: case study on 19 flats

The LCA method will be applied to 19 housing units (flats) in a single, Z-shaped building. Based on the calculation and interpretation of the eco-scores of the materials used, alternatives will be suggested to lower the overall environmental impact of the housing units. The case study aims at maintaining the assumed *K* and *E*-value, in order to obtain similar results with regard to energy consumption and living comfort.

Based on discussion with low-energy building experts and architects, the main parameters investigated in this study are variations of the insulation materials of the flat roof, the floors and the exterior walls and the other materials used for the exterior and interior walls. For each of these elements, the basic configuration will be compared to one or a few alternatives in terms of their overall environmental impact.

The choice of the parameters is directly derived from the properties of the structure of the flats, with focus on the adaptability of materials. Since this is a timber frame with a thickness of 14 cm, the insulation can be changed freely without affecting the structure. The same goes for the covering of this frame and the non-bearing interior walls. Other researches have investigated the differences between building concepts, like timber frame versus concrete structures [14] or passive versus standard dwellings [4,15]. As the goal of this research is to execute a material optimization, there is opted to examine parameters that do not change the structure as radically as within the mentioned researches. Nevertheless these non-bearing elements still deliver an important contribution to the total environmental burdens.

In the basic configuration of the flats, wooden framing construction is used. The flat roof is insulated using 0.09 m polyurethane (PUR), while for the floor 0.06 m PUR is used. The 0.15 m oriented strand board (OSB) exterior walls are insulated using 0.14 m rock wool. The interior walls consist of 0.015 m OSB-plate, 0.09 m rock wool insulation and 0.012 m plasterboard. The characteristics of this basic configuration can be found in Table 1.

The configuration of alternative materials will be chosen in order to obtain (at least) equal insulation performance. However, when calculating the minimal thickness of alternative materials to obtain the same degree of insulation (using $D = R \times \lambda$, where D is the material thickness in meters, R is the heat resistance in m^2 K/W and λ is the coefficient of heat conductivity), the thickness obtained might not be available for commercial use. In some cases, thicker material will be required, thus leading to a better insulation performance. Alternatively, this leads to an excessive use of the materials, thereby deteriorating the eco-score and increasing the overall weight of the materials.

With regard to the insulation of the flat roof, four alternatives are compared to the original 0.09 m PUR. The results are presented in Table 2. Three of the alternatives (rock wool, polystyrene foam and vermiculite) give occasion to a rise of the eco-impact. The use of vermiculite as roof insulation should be avoided, given the large quantity necessary to obtain a similar insulation performance and subsequent additional weight. Despite the larger weight when compared to PUR, the use of glass wool has a significant impact on the overall eco-score. Even though more glass wool has to be used than strictly necessary to obtain the same degree of insulation (0.12 m instead of 0.11), the eco-score is more than 76% lower than when PUR is used.

A second parameter that is relatively easy to vary without substantial redesign of the housing unit is the insulation of the exterior walls. As alternative for rock wool, the same alternatives as for the roof insulation are evaluated (see Table 3). Unsurprisingly, similar effects were found. Replacing the 0.14 m rock wool insulation with 0.12 m glass wool leads to a reduction of more than 79% of the eco-score. Again, the use of vermiculite is deemed undesirable, given the doubling of the thickness required (0.28 m vermiculite instead of 0.14 m rock wool).

In the original configuration, a 0.015 m OSB board was used both at the exterior and interior side of the exterior walls. The worst alternative is the use of particle boards, which more than double the eco-score (see Table 4). The best alternative turns out to be soft board, which lowers the eco-score with more than 76%.

The original interior walls used wooden framing construction. In the wooden skeleton, 0.09 m rock wool insulation is applied. On both sides, 0.015 m OSB and 0.012 m plaster boards were added. If this construction method would be replaced by walls out of 0.10 m plaster blocks, without any additional insulation, a huge reduction of the eco-score can be realised (−98.54%). However, the overall weight of the plaster block walls is significantly higher (Table 5).

These results lead to an optimal configuration for the 19 flats. Table 6 gives an overview, which leads to a reduction of almost 99% of the total eco-score. The matter concerns the total eco points for the production of the materials used in the two configurations. On all four aspects, a significant reduction is possible compared to the frequently used materials and configurations. Both architects and customers should be aware of the potential impact of their material choices.

Table 7 gives an overview of the total eco-score of the flats, including the production of the total bill of materials, the environmental impact of the flat use and the end-of-life aspects. A striking aspect of the results is the low share of the use phase, which contributes less than 1%. Since the building is a passive house, no heating system is installed, which explains mainly this low impact. The investigated elements are the use of electricity and the land use of the building. The water and gas consumption and maintenance is excluded from the results, because they depend largely on the behavior of the inhabitants and lack of data. It is obvious that the results are an underestimation of the ecological burdens, but a deeper investigation is beyond the scope of this research. Furthermore, the use phase is the same for all scenarios and thus has no influence on the results. Although use phase is simplified, other researches came to similar conclusions about the significant decrease of the use phase when talking about low energy dwellings. Blengini et al. states that when comparing a low energy and a standard dwelling in Italy, there is a potential for reducing the impact of the use phase with 90%. Although this generates an increase in the other phases, the benefit when considering the whole life cycle is only a reduction of 50% [16]. Adalberth et al. notes that the heating is responsible for 85% of total energy consumption during the use phase [17].

A comparison is made between waste dumping versus recycling of the building materials. The total difference between the original configuration of the flats and the eco-optimal configuration amounts 3.81% in case of waste dumping and 3.87% in case of waste recycling. However, the end-of-life impact of the eco-optimal flats is between 12 and 14% higher compared to the original configuration. This is mainly due to the high impact of dumping or recycling the plaster blocks. However, the overall eco-score of the optimized flats leads to a substantial lower environmental impact. The total share of the investigated parameters in the original configuration is about 5% of the total impact. Nevertheless, these non-structural elements can entail a large reduction in ecological impact within the same building concept. Comparison of materials and careful analysis potentially bear fruit.

Yet, these results only take the environmental impact into consideration. Other reflections play an equally important, if not more important, role in the final decision making process. For many people, the economic aspect (costs related to the different materials) prevails over environmental considerations. In this regard, an important role is put aside for public policy makers, who should find ways to stimulate the choice for the most environmental-friendly materials.

A second reflection on the results relates to implications for the building structure. Overall, the more environmental-friendly materials give occasion to a higher overall weight. Future research should address the issue and evaluate the effect on the required building structure. If the latter should be strengthened, the positive impact of using more eco-friendly materials could be undone by having to use a stronger building structure.

4. Discussion and implications

The sustainable housing concept bears many elements and parameters, which cannot all be investigated in a single study. This paper has tried to deepen our understanding and knowledge on the concept by performing a Life Cycle Assessment (LCA) on a single housing case study, namely 19 low-energy flats in a single building. Within the scope of the study, the Eco-indicator'99 method has been applied to find the best design setting and material choice for insulating materials and two distinct post-usage

Table 1
Original materials.

Description	Material	Thickness (m)	Quantity (m^2)	Quantity (m^3)	Quantity (kg)	Eco-score
Insulation flat roof	PUR	0.090	1637	147.33	5,893.2	2,510,503
Insulation floor	PUR	0.060	2170	130.2	5,208	2,229,024
Insulation exterior walls	Rock wool	0.140	2016	282.24	19,756.8	24,419,405
Exterior walls	OSB	0.150	4032	60.48	36,228	1,251,936,000
Interior walls	Wooden framing[a]	0.144			77,827	1,864,054,384

[a] 0.09 m rock wool + 0.015 m OSB-plate (2×) + 0.012 m plaster board (2×).

Table 2
Insulation of the flat roof.

Material	Minimal thickness (m)	Thickness (m)	Quantity (m^2)	Quantity (m^3)	Quantity (kg)	Eco-score	Change (%)
PUR	0.090	0.090	1637	147.330	5,893.20	2,510,503	
Rock wool	0.121	0.140	1637	229.180	16,043.00	2,823,498	+12.47
Glass wool	0.110	0.120	1637	180.070	9,822.00	579,498	−76.92
Polystyrene foam	0.114	0.120	1637	186.618	4,911.00	3,260,904	+29.89
Vermiculite	0.277	0.277	1637	453.122	31,741.43	2,729,763	+8.73

Table 3
Insulation of the exterior walls.

Material	Minimal thickness (m)	Thickness (m)	Quantity (m^2)	Quantity (m^3)	Quantity (kg)	Eco-score	Change (%)
Rock wool	0.140	0.14	2016	282.240	19,756.8	3,477,197	
Glass wool	0.112	0.12	2016	225.792	12,096.0	713,664	−79.48
Polystyrene foam	0.116	0.12	2016	232.840	6,048.0	4,015,872	+15.49
Vermiculite	0.280	0.28	2016	564.480	39,513.6	3,398,170	−2.30
PUR	0.091	0.10	2016	183.450	8,064.0	3,435,264	−1.20

Table 4
Exterior walls: boards.

Material	Minimal thickness (m)	Thickness (m)	Quantity (m^2)	Quantity (m^3)	Quantity (kg)	Eco-score	Change (%)
OSB	0.01500	0.015	4.032	60.480	36,228.0	1,251,936,000	
Medium-Density Fibreboard (MDF)	0.01153	0.012	4.032	48.384	29,030.4	1,117,670,400	−10.72
Particle board	0.02650	0.028	4.032	112.890	180,624.0	4,082,102,400	+226.06
Soft board	0.00800	0.010	4.032	40.320	16,128.0	295,142,400	−76.43

Table 5
Interior walls.

Material	Minimal thickness (m)	Thickness (m)	Quantity (m^2)	Quantity (m^3)	Quantity (kg)	Eco-score	Change (%)
Wooden framing[a]	0.144	0.144			77,827	1,864,054,384	
Plaster blocks	0.100	0.100			299,565	27,260,415	−98.54

[a] 0.09 m rock wool + 0.015 m OSB-plate (2×) + 0.012 m plaster board (2×).

handling methods: waste disposal (through dumping or burning) and waste recycling. The results indicate that for the production phase, there is a potential for reducing the environmental impact of almost 4.5% when only optimizing a selection of non-bearing materials which can easily be changed without affecting the structure. Furthermore, when also taking the end-of-life into account, the results indicate that waste recycling, to the extent possible for the materials, generally is the best option in terms of environmental impact. In case of waste dumping, the EOL eco-score increases with 14.02%, but when considering the total life cycle there is still a gain of 3.81%. If we assume that the whole building will be recycled, the EOL eco-score increases less, namely by 12.26%. Over the total life cycle this provides a net reduction of 3.87%. Although the total impact decreases, the impact of the end-of-life phase rises, which is mainly due to the high impact of dumping or recycling the plaster blocks. Within the scope of the study however, only two extremes have been investigated: waste dumping of all materials and waste recycling of all materials (if possible). Although recycling seems to offer the lowest eco-score, further research should indicate whether there is an optimal mix (i.e. can the situation further be enhanced if some materials as disposed and some recycled?). This search for the optimal mix is unique for every setting but

Table 6
Comparison original and eco-optimal flats.

Original configuration	Eco-optimal flats		
Original materials	Eco-score production original materials	Best alternative materials	Eco-score production best alternative materials
PUR (roof)	2,510,503	Glass wool	579,498
Rock wool (exterior wall)	3,477,197	Glass wool	713,664
OSB (exterior wall)	1,251,936,000	Soft board	295,142,400
Interior wall	1,864,054,384	Plaster blocks	27,260,415
Sub-total eco-score production	3,121,978,084	−98,96%	323,695,977

Table 7
Comparison waste disposal and recycling.

	Eco-score original configuration	Difference (%)	Eco-score eco-optimal flats
Waste dumping			
Eco-score production	62,958,053,986	−4.44%	60,159,771,879
Eco-score use	60,682,950	=	60,682,950
Eco-score end-of-life	2,220,292,286	+14.02%	2,531,563,088
Total eco-score	65,239,029,222	−3.81%	62,752,017,917
Recycling			
Eco-score production	62,958,053,986	−4.44%	60,159,771,879
Eco-score use	60,682,950	=	60,682,950
Eco-score end-of-life	2,220,292,286	+12.26%	2,492,491,291
Total eco-score	65,239,029,222	−3.87%	62,712,946,120

should allow architects to find the design with the lowest environmental impact in terms of eco-score.

As the analysis indicated, production of the materials turns out to be the element generating the largest impact on the final eco-score. The choice of materials is therefore a key parameter in minimising the environmental impact of housing units. Apparently, as the eco-score of the materials' production is responsible for more than 95% of total eco-score, this result underpinned our choice to focus on comparing alternative materials and evaluate their impact on the final eco-score of one building design. A major implication of this result concerns architects and customers. Their final choice should primarily be based on material choices with a minimal environmental impact during their production process instead of focusing on the most optimal design. This does not mean that environmental-friendly design do not offer any added value with regard to the issue, but the reward in terms of eco-score if searching for the most appropriate design given some material choice is much smaller than if searching for the best materials (i.e. those with the lowest production eco-score).

In almost every design, building or production process, outcomes appear unwanted with regard to environmental considerations. However, the economic cost to repair or counter these unwanted effects rarely appear in the economic cost of the resulting goods or services. The internalisation is nevertheless crucial if our society wishes to enhance its sustainability on the long term, without burdening future generations. This aspect touches upon two discussion elements related to this study. As should be the case in all goods and services, the environmental costs of the building materials and processes should be reflected in their sales price and the manufacturers or service providers should be held responsible to repair or counter the environmental effects of their production processes. This would probably give occasion for sharp price increases as, similar to prior reasoning, the internalisation of environmental costs does not occur systematically actually.

Another discussion element resulting of the need for internalisation of environmental costs refers similarly to economic aspects of the housing industry. A big challenge for future research lies in coupling economic costs to environmental impact assessment methods, such as the Eco-indicator'99 method. Only then practitioners and policy makers will be able to evaluate an approach or policy on its environmental impact and its economic feasibility simultaneously.

4.1. Limitations

Some of the major limitations relate to the specific set-up of the study. In the current research setting, 19 flats have been analysed. Further research should elaborate on these results to analyse different setting (houses, commercial buildings, etc.). A second limitation relates to the progress of the project in reality. The calculations have been based on estimations of material use instead of their effective use. Differences might occur do to wasting of materials during the actual execution of the project. Additionally, not all parameters have been taken into account, as some finishing elements (e.g. choice of kitchen, bathroom and so on) had not been made yet at the time of the design as the customer had the opportunity to adapt these elements to their personal taste and preference. Lastly, the research excluded the impact of transportation on the environment. As this parameter differs substantially between building projects, we have opted not to include it in the calculations. As a consequence, the results are an underestimation of real impact of the project on the environment.

As mentioned earlier, the Eco-indicator method has some inherent limitations as well. As the method is relatively young, it is currently still partially under development and does not yet include all environmental impacts such as the influence of phosphates on underground and surface water.

4.2. Future research opportunities

The study presented in this paper is just a first step in evaluating the current building concepts and methods on their environmental impact. Future research could be performed to deepen our understanding of similar building concepts in other settings (houses, commercial and industrial buildings). Another major opportunity lies in relating eco-indicator methods to their economic implications in finding an acceptable equilibrium between both elements. The trade-off between both elements, eventually in combination with upper and/or lower bounds on both dimensions, strongly influences its applicability in practice. If the construction industry and individual consumers are to adopt the method and incorporate the idea of sustainable housing actively in their decision process, the link between environmental impact and cost implications needs to be established and communicated. The last element might even be the most important.

Overall, our results confirm the impact and importance of building material choices on the environmental impact. Using a case study of 19 low-energy housing units, the overall eco-score after optimization of the material choice was reduced with almost 4%. This significant reduction mainly relates to the environmental impact of the production of the materials.

References

[1] B. Ewing, D. Moore, S. Goldfinger, A. Oursler, A. Anders Reed, M. Wackernagel, Ecological Footprint Atlas 2010, Global Footprint Network, Oakland, CA, USA, 2010.
[2] A. Audenaert, S.H. De Cleyn, B. Vankerckhove, Economic analysis of passive houses and low-energy houses compared to standard houses, Energy Policy 26 (1) (2008) 47–55.
[3] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, et al., Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2002.
[4] G.A. Blengini, T. Di Carlo, The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy and Buildings 42 (2009) 869–880.

[5] I. Satori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: a review article, Energy and Buildings 39 (2006) 249–257.
[6] J.B. Guinée, H. Reinout, G. Huppes, A. Zamagni, A. Masoni, T. Ekvall, T. Rydberg, Life cycle assessment: past, present, and future, Environmental Science & Technology 45 (1) (2011) 90–96.
[7] ISO 14040, Environmental Management – Life Cycle Assessment – Principles and Framework, International Organization for Standardisation, Geneva, Switzerland, 2006.
[8] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle energy analysis of buildings: an overview, Energy and Buildings 42 (2010) 1592–1600.
[9] O. Ortiz, F. Catsells, G. Sonnemann, Sustainability in the construction industry: a review of recent developments based on LCA, Construction and Building Materials 23 (2009) 28–39.
[10] G.A. Blengini, (12 March, 2008) Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy, Building and Environment 44 (2009) 319–330.
[11] M. Goedkoop, R. Spriensma, The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment—Methodology Report, Pré Consultants B.V., Amersfoort, The Netherlands, 2001.
[12] Eco-Indicator 99 Manual for Designers: A Damage Oriented Method for Life Cycle Impact Assessments, Ministery of Housing, Spatial Planning and Environment, Den Haag, The Netherlands, 2000.
[13] G.A. Blengini, Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy, Building and Environment 44 (2008) 319–330.
[14] N. Mithraratne, B. Vale, Life cycle analysis model for New Zealand houses, Building and Environment 39 (2004) 483–492.
[15] B.L.P. Peuportier, Life cycle assessment applied to the comparative evaluation of single family houses in the French context, Energy and Buildings 33 (2001) 443–450.
[16] G.A. Blengini, T. Di Carlo, Energy-saving policies and low-energy residential buildings: an LCA case study to support decision makers in Piedmont (Italy), The International Journal of Life Cycle Assessment 15 (2010) 652–665.
[17] K. Adelberth, A. Almgren, E.H. Peterson, Life cycle assessment of four multi family buildings, The International Journal of Low Energy and Sustainable Buildings 2 (2001) 1–21.